

# D-Meson Azimuthal Anisotropy in Midcentral Pb-Pb Collisions at $\sqrt{s_{NN}}=5.02$ TeV

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***D*-Meson Azimuthal Anisotropy in Midcentral Pb-Pb Collisions at  $\sqrt{s_{NN}} = 5.02$  TeV**S. Acharya *et al.*\*  
(ALICE Collaboration) (Received 23 July 2017; revised manuscript received 16 November 2017; published 9 March 2018)

The azimuthal anisotropy coefficient  $v_2$  of prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons was measured in midcentral (30%–50% centrality class) Pb-Pb collisions at a center-of-mass energy per nucleon pair  $\sqrt{s_{NN}} = 5.02$  TeV, with the ALICE detector at the LHC. The  $D$  mesons were reconstructed via their hadronic decays at midrapidity,  $|y| < 0.8$ , in the transverse momentum interval  $1 < p_T < 24$  GeV/ $c$ . The measured  $D$ -meson  $v_2$  has similar values as that of charged pions. The  $D_s^+$   $v_2$ , measured for the first time, is found to be compatible with that of nonstrange  $D$  mesons. The measurements are compared with theoretical calculations of charm-quark transport in a hydrodynamically expanding medium and have the potential to constrain medium parameters.

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Quantum chromodynamics predicts that strongly interacting matter under extreme conditions of a high temperature and energy density undergoes a transition from the hadronic phase to a color-deconfined medium, called quark-gluon plasma (QGP) [1–4]. Heavy-ion collisions at ultrarelativistic energies provide suitable conditions for the QGP formation and for characterizing its properties.

Heavy quarks (charm and beauty) are predominantly produced in hard scatterings before the QGP formation [5,6]. Therefore, they experience all stages of the medium evolution, interacting with its constituents via elastic [7] and inelastic (radiation of gluons) [8,9] processes (see [6,10] for recent reviews).

Evidence of in-medium interactions and energy loss of charm quarks is provided by the strong modification of the transverse momentum ( $p_T$ ) distributions of heavy-flavor hadrons in heavy-ion collisions with respect to  $pp$  collisions. A large suppression of heavy-flavor hadron yields was observed for  $p_T > 4$ –5 GeV/ $c$  in central nucleus-nucleus collisions at the RHIC [11–14] and the LHC [15–19].

Measurements of anisotropies in the azimuthal distribution of heavy-flavor hadrons assess the transport properties of the medium. The collective dynamics of the expanding medium converts the initial-state spatial anisotropy [20] into final-state particle momentum anisotropy. This anisotropy is characterized by the Fourier coefficients  $v_n$  of the distribution of the particle azimuthal angle  $\varphi$  relative to

the initial-state symmetry plane angle  $\Psi_n$  (for the  $n$ th harmonic) [21,22]. In noncentral collisions, the largest contribution corresponds to  $v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$ , called elliptic flow [22,23]. The  $D$ -meson  $v_2$  at low  $p_T$  provides insight into the possible collective flow imparted by the medium to charm quarks [24], while at high  $p_T$  it is sensitive to the path-length dependence of parton energy loss [25,26]. At low and intermediate  $p_T$ , a fraction of charm quarks could hadronize via recombination with light quarks from the medium, leading to an increase of the  $D$ -meson  $v_2$  with respect to that of charm quarks [27–29]; the comparison of the  $v_2$  of  $D$  mesons without and with strange-quark content could be sensitive to these effects and to the charm coupling to the QGP and hadronic matter [30].

A positive heavy-flavor elliptic flow was observed in Au-Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [11,31,32] and in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV [19,33–36]. Calculations based on heavy-quark transport in a hydrodynamically expanding medium describe the measurements [37–46]. Precise measurements of heavy-flavor  $v_2$  constrain model parameters, e.g., the heavy-quark spatial diffusion coefficient  $D_s$  in the QGP, which is related to the relaxation (equilibration) time of heavy quarks  $\tau_Q = (m_Q/T)D_s$ , where  $m_Q$  is the quark mass and  $T$  is the medium temperature [47].

In this Letter, we report on the  $v_2$  of  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and, for the first time at the LHC,  $D_s^+$  mesons, and their antiparticles, in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, for the 30%–50% centrality class. The analysis uses Pb-Pb collisions collected with the ALICE detector [48,49] in 2015. The interaction trigger consisted in coincident signals in the two scintillator arrays of the V0 detector, covering full azimuth in the pseudorapidity ( $\eta$ ) regions  $-3.7 < \eta < -1.7$  and  $2.8 < \eta < 5.1$ . Events from beam-gas interactions are removed using time information from the V0 and the neutron zero-degree calorimeters.

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Only the events with a primary vertex reconstructed within  $\pm 10$  cm from the detector center along the beam direction are analyzed. Events are selected in the centrality class 30%–50%, defined in terms of percentiles of the hadronic Pb-Pb cross section, using the amplitude of the V0 signals [50,51]. The number of selected events is  $20.7 \times 10^6$ , corresponding to an integrated luminosity  $L_{\text{int}} \approx 13 \mu\text{b}^{-1}$  [51].

The  $D$  mesons and their antiparticles are reconstructed using the decay channels  $D^0 \rightarrow K^- \pi^+$ ,  $D^+ \rightarrow K^- \pi^+ \pi^+$ ,  $D^{*+} \rightarrow D^0 \pi^+$ , and  $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$ . The analysis procedure [34,52] searches for decay vertices displaced from the interaction vertex, exploiting the mean proper decay lengths of about 123, 312, and  $150 \mu\text{m}$  of  $D^0$ ,  $D^+$ , and  $D_s^+$  mesons, respectively [53]. Charged-particle tracks are reconstructed using the inner tracking system (ITS) and the time projection chamber (TPC), which are located within a solenoid magnet that provides a 0.5 T field, parallel to the beam direction.  $D^0$ ,  $D^+$ , and  $D_s^+$  candidates are defined using pairs and triplets of tracks with  $|\eta| < 0.8$ ,  $p_T > 0.4 \text{ GeV}/c$ , 70–159 TPC space points, and 2–6 hits in the ITS (at least one in the two innermost layers).  $D^{*+}$  candidates are formed by combining  $D^0$  candidates with tracks with  $|\eta| < 0.8$ ,  $p_T > 0.1 \text{ GeV}/c$ , and at least three ITS hits. The selection of tracks with  $|\eta| < 0.8$  limits the  $D$ -meson acceptance in rapidity, which varies from  $|y| < 0.6$  for  $p_T = 1 \text{ GeV}/c$  to  $|y| < 0.8$  for  $p_T > 5 \text{ GeV}/c$ . The main variables used to select the  $D$  candidates are the separation between the primary and decay vertices, the displacement of the tracks from the primary vertex, and the pointing of the reconstructed  $D$ -meson momentum to the primary vertex. For the selection of  $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$  decays, one of the two pairs of opposite-sign tracks must have an invariant mass compatible with the  $\phi$ -meson mass [53]. Further background reduction results from the particle identification. A  $\pm 3\sigma$  window around the expected mean values of the specific ionization energy loss  $dE/dx$  in the TPC gas and time of flight from the interaction point to the time-of-flight (TOF) detector is used for each track, where  $\sigma$  is the resolution on the two variables. For  $D_s^+$  candidates, tracks not matched to a hit in the TOF (mostly at low momentum) are required to have a  $2\sigma$  compatibility with the expected  $dE/dx$  in the TPC. These selections result in signal-to-background ratios between 0.04 and 2.8 and a statistical significance between 3 and 20, depending on the  $D$ -meson species and  $p_T$ .

The second harmonic symmetry plane  $\Psi_2$  is estimated, for each collision, by the event plane (EP) angle, denoted  $\psi_2$ , using the signals produced by charged particles in the eight azimuthal sectors of each V0 array. Effects of nonuniform V0 acceptance are corrected for using the gain equalization method [54]. The  $v_2$  was calculated by classifying  $D$  mesons in two groups, according to their azimuthal angle relative to the EP  $\Delta\varphi = \varphi_D - \psi_2$ : in plane

( $[-(\pi/4), (\pi/4)]$  and  $[(3\pi/4), (5\pi/4)]$ ) and out of plane ( $[(\pi/4), (3\pi/4)]$  and  $[(5\pi/4), (7\pi/4)]$ ). Integrating the  $dN/d\varphi$  distribution in these two  $\Delta\varphi$  intervals,  $v_2$  can be expressed as [34]:

$$v_2\{\text{EP}\} = \frac{1}{R_2} \frac{\pi N_{\text{in-plane}} - N_{\text{out-of-plane}}}{4 N_{\text{in-plane}} + N_{\text{out-of-plane}}}, \quad (1)$$

where  $N_{\text{in-plane}}$  and  $N_{\text{out-of-plane}}$  are the  $D$ -meson yields in the two  $\Delta\varphi$  intervals. The factor  $(1/R_2)$  is the correction for the resolution in the estimation of the symmetry plane  $\Psi_2$  via the EP angle  $\psi_2$ . It is calculated using three subevents of charged particles in the V0 and in the positive and negative  $\eta$  regions of the TPC [22]. The separation of at least 0.9 units of pseudorapidity ( $|\Delta\eta| > 0.9$ ) between the  $D$  mesons and the particles used in the  $\psi_2$  calculation suppresses nonflow contributions to  $v_2$  (i.e., correlations not induced by the collective expansion but rather by decays and jet production).

Simulations showed that the  $D$ -meson reconstruction and selection efficiencies do not depend on  $\Delta\varphi$  [34]; therefore, Eq. (1) can be applied using the  $D$ -meson raw yields, without an efficiency correction. The raw yields were obtained from fits to the  $D^0$ ,  $D^+$ , and  $D_s^+$  candidate invariant-mass distributions and to the mass difference  $\Delta M = M(K\pi\pi) - M(K\pi)$  distributions for  $D^{*+}$  candidates. In the fit function, the signal was modeled with a Gaussian and the background with an exponential term for  $D^0$ ,  $D^+$ , and  $D_s^+$  candidates and with the function  $a\sqrt{\Delta M - m_\pi} e^{b(\Delta M - m_\pi)}$  for  $D^{*+}$  candidates. The mean and the width of the Gaussian were fixed to those obtained from a fit to the sum of the invariant-mass distributions in the two  $\Delta\varphi$  intervals, where the signal has a higher statistical significance. In the  $D^0$  invariant-mass fit, the contribution of signal candidates with the wrong  $K$ - $\pi$  mass assignment (about 2%–5% of the raw signal depending on  $p_T$ ) was taken into account by including an additional term, parametrized from simulations with a double-Gaussian shape, in the fit function [34].

The measured  $D$ -meson yield includes the contributions of prompt  $D$  mesons, from  $c$ -quark hadronization or strong decays of  $D^*$  states, and of feed-down  $D$  mesons from beauty-hadron decays. The observed  $v_2$ , measured with Eq. (1), is a linear combination of the prompt and feed-down contributions:  $v_2^{\text{obs}} = f_{\text{prompt}} v_2^{\text{prompt}} + (1 - f_{\text{prompt}}) v_2^{\text{feed-down}}$ , where  $f_{\text{prompt}}$  is the fraction of prompt  $D$  mesons in the raw yields and  $v_2^{\text{feed-down}}$  is the elliptic flow of  $D$  mesons from beauty-hadron decays. To calculate  $v_2^{\text{prompt}}$ , a hypothesis on  $v_2^{\text{feed-down}}$  is used. The measured  $v_2$  of nonprompt  $J/\psi$  [19] and the available model calculations [37,55,56] suggest that  $0 < v_2^{\text{feed-down}} < v_2^{\text{prompt}}$ . Assuming a uniform probability distribution of  $v_2^{\text{feed-down}}$  in this interval, the central value for  $v_2^{\text{prompt}}$  is calculated considering  $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$ ; thus,  $v_2^{\text{prompt}} = 2v_2^{\text{obs}}/(1 + f_{\text{prompt}})$ . The  $f_{\text{prompt}}$  fraction is estimated, as a function of  $p_T$ , as described in Ref. [57], using

the FONLL [58] calculation for the beauty-hadron cross section, the beauty-hadron decay kinematics from EvtGen [59], the reconstruction efficiencies for feed-down  $D$  mesons from the simulation, and a hypothesis for the nuclear modification factor of the feed-down  $D$  mesons,  $R_{AA}^{\text{feed-down}}$ . The nuclear modification factor is defined as the ratio of the  $p_T$ -differential yields in nucleus-nucleus and  $pp$  collisions scaled by the average number of nucleon-nucleon collisions in the considered centrality class [60]. By comparison of the  $R_{AA}$  of prompt  $D$  mesons [61] and  $J/\psi$  mesons from beauty-hadron decays [19] in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, the assumptions  $R_{AA}^{\text{feed-down}} = 2R_{AA}^{\text{prompt}}$  for nonstrange  $D$  mesons and  $R_{AA}^{\text{feed-down}} = R_{AA}^{\text{prompt}}$  for the  $D_s^+$  meson are made to compute  $f_{\text{prompt}}$ .

The systematic uncertainty from feed-down on  $v_2^{\text{prompt}}$  was estimated by varying the central value of  $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$  by  $\pm v_2^{\text{prompt}}/\sqrt{12}$ , corresponding to  $\pm 1$  rms of a uniform distribution in  $(0, v_2^{\text{prompt}})$ . The uncertainty on  $f_{\text{prompt}}$  was obtained from the variation of the FONLL calculation parameters and from the variation of the  $R_{AA}^{\text{feed-down}}$  hypothesis in  $1 < R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}} < 3$  for nonstrange  $D$  mesons [15] and  $\frac{1}{3} < R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}} < 3$  for  $D_s^+$  mesons [52]. The value of the absolute systematic uncertainty from feed-down ranges from 0.001 to 0.030.

The other sources of systematic uncertainty are related to the signal extraction from the invariant-mass distribution, nonflow effects, and centrality dependence in the EP resolution correction  $R_2$ .

The signal extraction uncertainty was estimated by varying the background fit function and leaving the Gaussian width and mean as free parameters in the fit. Furthermore, an alternative method for the yield extraction based on counting the histogram entries in the signal invariant-mass region, after subtracting the background estimated from a fit to the sidebands, was considered. The absolute systematic uncertainties on  $v_2$  due to the yield extraction range from 0.005 to 0.040 for  $D^0$ ,  $D^+$ , and  $D^{*+}$  and from 0.015 to 0.070 for  $D_s^+$  mesons. As a check of a possible efficiency dependence on  $\Delta\phi$ , the analysis was repeated with different selection criteria, and no systematic effect was observed.

The EP resolution correction  $R_2$  depends on collision centrality [34]. The value used in Eq. (1) was computed assuming a uniform distribution of the  $D$ -meson yield within the centrality class. This value was compared with those obtained from the weighted averages of the  $R_2$  values in narrow centrality intervals, using as weights either the  $D$ -meson yields or the number of nucleon-nucleon collisions. In addition, to account for the presence of possible nonflow effects in the estimation of  $R_2$ , its value was recomputed using two different pseudorapidity gaps between the sub-events of the TPC tracks with positive or negative  $\eta$ . A systematic uncertainty of 2% on  $R_2$  was estimated.

The  $v_2$  of prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons in the 30%–50% centrality class is shown in Fig. 1. The symbols

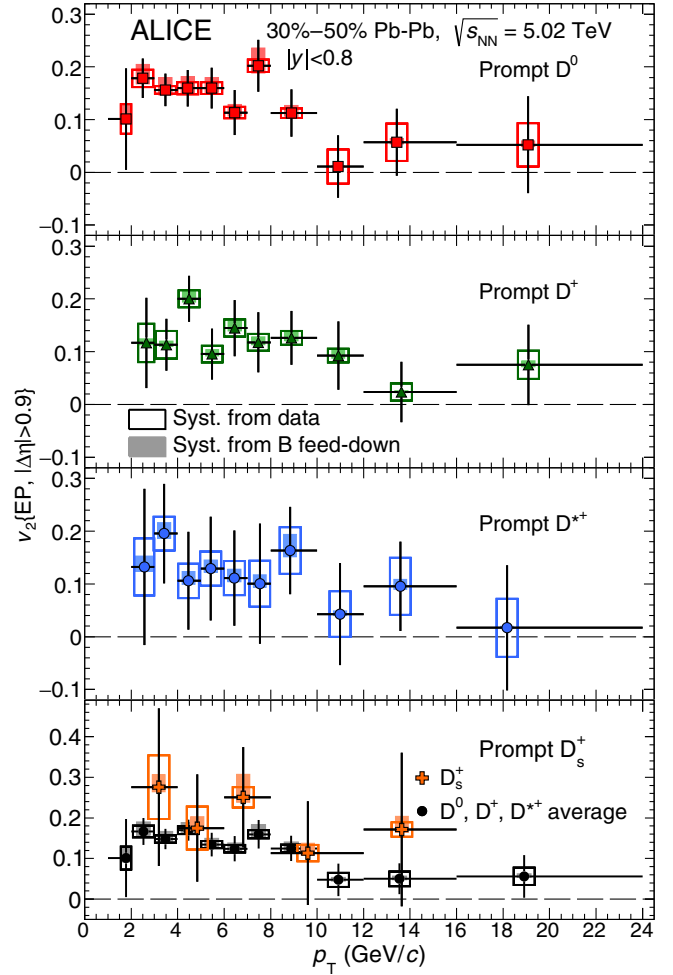


FIG. 1. Elliptic flow coefficient as a function of  $p_T$  for prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons and their charge conjugates for Pb-Pb collisions in the centrality class 30%–50%. The bottom panel also shows the average  $v_2$  of  $D^0$ ,  $D^+$ , and  $D^{*+}$ . Vertical bars represent the statistical uncertainty, and empty boxes the systematic uncertainty associated with the  $D$ -meson anisotropy measurement and the event-plane resolution. Shaded boxes show the feed-down uncertainty.

are positioned at the average  $p_T$  of the reconstructed  $D$  mesons: this value was determined as the average of the  $p_T$  distribution of candidates in the signal invariant-mass region, after subtracting the contribution of the background candidates estimated from the sidebands. The  $v_2$  of  $D^0$ ,  $D^+$ , and  $D^{*+}$  are consistent, and they are larger than zero in  $2 < p_T < 10$  GeV/c. The  $D^0$   $v_2$  is compatible with the measurement by the CMS Collaboration [62]. The average of the  $v_2$  measurements for  $D_s^+$  mesons in the three  $p_T$  intervals within  $2 < p_T < 8$  GeV/c is positive with a significance of  $2.6\sigma$ , where  $\sigma$  is the uncertainty of the average  $v_2$ , calculated using quadratic propagation for the statistical and uncorrelated systematic uncertainties (signal extraction) and linear propagation for the correlated systematic uncertainties ( $R_2$  and feed-down correction). The average  $v_2$  and  $p_T$  of  $D^0$ ,  $D^+$ , and  $D^{*+}$ ,

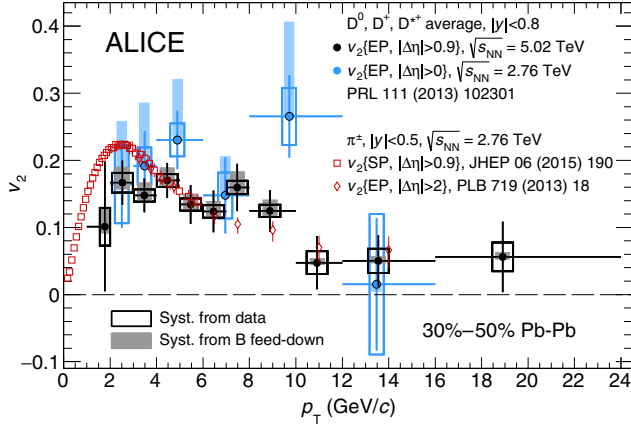


FIG. 2. Average of  $D^0$ ,  $D^+$ , and  $D^{*+}$   $v_2$  as a function of  $p_T$  at  $\sqrt{s_{NN}} = 5.02$  TeV, compared with the same measurement at  $\sqrt{s_{NN}} = 2.76$  TeV [ $L_{int} \approx 6 \mu\text{b}^{-1}$ ] [33], which has uncertainties larger by a factor of about 2 compared to the new result at 5.02 TeV. Note that the vertexing and tracking performance improved in 2015, and in Ref. [33] the correction for feed-down was made with the assumption  $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$ . The assumption used in the present analysis,  $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$ , would increase the values at  $\sqrt{s_{NN}} = 2.76$  TeV by about 10%.

shown in the bottom panel in Fig. 1, was computed using the inverse of the squared statistical uncertainties as weights. The systematic uncertainties were propagated treating the  $R_2$  and feed-down contributions as correlated among  $D$ -meson species.

Figure 2 shows that the average  $v_2$  of  $D^0$ ,  $D^+$ , and  $D^{*+}$  at  $\sqrt{s_{NN}} = 5.02$  TeV is compatible with the same measurement at  $\sqrt{s_{NN}} = 2.76$  TeV ( $L_{int} \approx 6 \mu\text{b}^{-1}$ ) [33], which has uncertainties larger by a factor of about 2 compared to the new result at 5.02 TeV. Note that the vertexing and tracking performance improved in 2015, and in Ref. [33] the correction for feed-down was made with the assumption  $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$ . The assumption used in the present analysis,  $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$ , would increase the values at  $\sqrt{s_{NN}} = 2.76$  TeV by about 10%.

The average  $D$ -meson  $v_2$  is also compared with the  $\pi^\pm$   $v_2$  at  $\sqrt{s_{NN}} = 2.76$  TeV measured with the EP method [63,64] considering a pseudorapidity separation of two units between  $\pi^\pm$  and the particles used to measure the EP angle, and the scalar-product method [65], also based on two-particle correlations. The comparison of the  $D$ -meson  $v_2$  at  $\sqrt{s_{NN}} = 5.02$  TeV and of the pion  $v_2$  at  $\sqrt{s_{NN}} = 2.76$  TeV is justified by the observation that the  $p_T$  differential  $v_2$  of charged particles, which is dominated by the pion component, is compatible at these two energies [66]. The  $D$ -meson  $v_2$  is similar to that of  $\pi^\pm$  in the common  $p_T$  interval (1–16 GeV/c), and it is lower in the interval below 4 GeV/c, the difference reaching about  $2\sigma$  in 2–4 GeV/c, where a mass ordering of  $v_2$  is observed for light-flavor hadrons and described by hydrodynamical calculations [65].

In Fig. 3, the average  $v_2$  of the three nonstrange  $D$ -meson species is compared with theoretical calculations that include a hydrodynamical model for the QGP expansion (models that lack this expansion underestimated the  $D$ -meson  $v_2$  measurements at  $\sqrt{s_{NN}} = 2.76$  TeV in

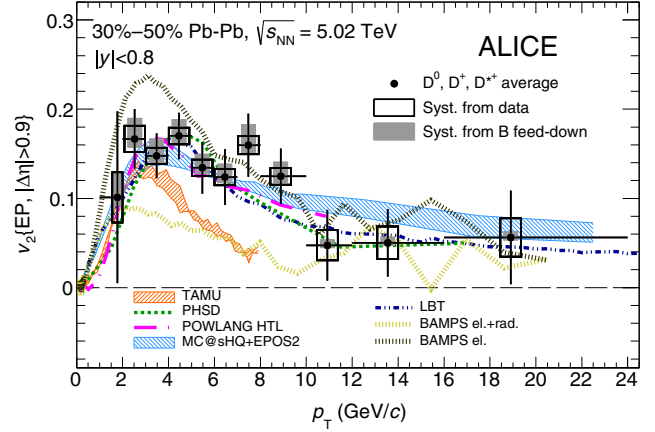


FIG. 3. Average of  $D^0$ ,  $D^+$ , and  $D^{*+}$   $v_2$  as a function of  $p_T$ , compared with model calculations [38,42–46].

$2 < p_T < 6$  GeV/c [34]). The BAMPS-el [44], POWLANG [45], and TAMU [38] calculations include only collisional (i.e., elastic) interaction processes, while the BAMPS-el+rad [44], LBT [46], MC@sHQ [43], and PHSD [42] calculations also include energy loss via gluon radiation. All calculations, with the exception of BAMPS, include hadronization via quark recombination, in addition to independent fragmentation. The MC@sHQ and TAMU results are displayed with their theoretical uncertainty band. All calculations provide a fair description of the nuclear modification factor of  $D$  mesons in central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV in  $1 < p_T < 8$  GeV/c [15].

The  $v_2$  measurement at  $\sqrt{s_{NN}} = 5.02$  TeV is described by most of these calculations, in which the interactions with the hydrodynamically expanding medium impart a positive  $v_2$  to charm quarks. The model-to-data consistency was quantified using the reduced  $\chi^2$  in the  $p_T$  interval where all calculations are available (2–8 GeV/c): The LBT, MC@sHQ, PHSD, and POWLANG models have  $\chi^2/\text{ndf} < 1$ , and the TAMU, BAMPS-el+rad, and BAMPS-el models have a  $\chi^2/\text{ndf}$  of 4.1, 6.7, and 1.9, respectively. The  $\chi^2$  calculation includes the data uncertainties and the model uncertainties when available. For BAMPS-el+rad, the low value of  $v_2$  is caused by the absence of the recombination contribution [44]. For TAMU, the rapid decrease of  $v_2$  with increasing  $p_T$  is due to the lack of radiative energy loss, which is also reflected in  $R_{AA}$  values larger than the measured ones at high  $p_T$  [15]. For most of these calculations, the medium effect on heavy quarks can be expressed using the dimensionless quantity  $2\pi TD_s(T)$  [47]. In the interval from the critical temperature for QGP formation  $T_c \approx 155$  MeV [2] to  $2T_c$ , the ranges of  $2\pi TD_s(T)$  are 1–2 for BAMPS-el, 6–10 for BAMPS-el+rad, 2–6 for LBT [67], 1.5–4.5 for MC@sHQ [6], 4–9 for PHSD [42], 7–18 for POWLANG [10], and 4–10 for TAMU [6]. The calculations that describe the data with  $\chi^2/\text{ndf} < 1$  use  $2\pi TD_s(T)$  in the range of 1.5–7 at  $T_c$ . Remarkably, this range is consistent with that obtained by the comparison of the  $D^0$   $v_2$  in Au-Au collisions at  $\sqrt{s_{NN}} = 200$  GeV to

model calculations [32], and it includes the values obtained by lattice QCD calculations [68,69] which are independent of the collision energy, because they encode a property of the medium evaluated at a fixed temperature. The corresponding thermalization time [47] for charm quarks is  $\tau_{\text{charm}} = (m_{\text{charm}}/T)D_s(T) \approx 3\text{--}14 \text{ fm}/c$  with  $T = T_c$  and  $m_{\text{charm}} = 1.5 \text{ GeV}/c^2$ . These values are comparable to the estimated decoupling time of the high-density system [70]. It should also be pointed out that the models differ in several aspects, related to the medium expansion and the heavy quark-medium interactions both in the QGP and in the hadronic phase.

In summary, we have presented a measurement of the elliptic flow  $v_2$  of prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ . The average  $v_2$  of nonstrange  $D$  mesons was measured with statistical and systematic uncertainties smaller by a factor about 2 with respect to our measurement at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ . The results at the two energies are compatible within statistical uncertainties. The  $D_s^+$   $v_2$  was for the first time measured at the LHC, although with a limited precision, and found to be compatible with that of nonstrange  $D$  mesons. The comparison of the  $D$ -meson  $v_2$  with that of pions and with model calculations indicates that low-momentum charm quarks take part in the collective motion of the QGP and that collisional interaction processes as well as the recombination of charm and light quarks both contribute to the observed elliptic flow. The calculations that describe the measurements use heavy-quark spatial diffusion coefficients in the range of  $2\pi TD_s(T) \approx 1.5\text{--}7$  at the critical temperature  $T_c$ .

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